Measurement of Transverse Single-Spin Asymmetries for J/ψ Production in Polarized $p+p$ Collisions at $\sqrt{s} = 200$ GeV

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Abstract.

In this paper the first measurement of transverse SSAs in J/ψ production is presented. The data were taken by the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) during the 2006 and 2008 polarized proton run at $\sqrt{s} = 200$ GeV. The p_T and x_F dependencies are studied, for rapidity regions of $-2.2 < y < -1.2$, $|y| < 0.35$, and $1.2 < y < 2.2$, and p_T up to 6 GeV/c. Results were obtained as a function of J/ψ transverse momentum and Feynman-x.

1. Introduction

Transverse single-spin asymmetries (SSAs) quantify the asymmetry of particle production relative to the plane defined by the transverse spin axis and the momentum direction of a polarized hadron. Large azimuthal transverse single-spin asymmetries of up to $\sim 40\%$ were first observed at large Feynman-x ($x_F = 2p_L/\sqrt{s}$, where p_L is the momentum along the beam direction) in pion production from transversely polarized proton-proton collisions at $\sqrt{s} = 4.9$ GeV in 1976 [1], contrary to theoretical expectations at the time [2], and subsequently observed in hadronic collisions over a range of energies extending up to $\sqrt{s} = 200$ GeV [3, 4, 5, 6, 7, 8, 9].

In order to describe the large transverse SSAs observed, two approaches have been developed since the 1990s. One approach requires higher-twist contributions in the collinear factorization scheme. This was first proposed by Qiu and Sterman for gluon exchange in the initial state [10] and by Kanazawa and Koike for exchange in the final state [11]. Gluon exchange in either the initial or final state leads to terms including multiparton correlation functions, which can generate a non-zero SSA. The other approach utilizes parton distribution functions and/or fragmentation functions that are unintegrated in the partonic transverse momentum, k_T; these functions are generally known as transverse-momentum-dependent distributions (TMDs). These two approaches have different but overlapping kinematic regimes of applicability and have been shown to correspond exactly in their region of overlap [12].

It was proposed in 2008 by Yuan [13] that within the framework of non-relativistic QCD (NRQCD) [14], the transverse SSA of J/ψ production can be sensitive to the J/ψ production mechanism, assuming a non-zero gluon Sivers function [15], which is a TMD that describes the correlation between the transverse spin of the proton and the k_T of the partons within it. Specifically, Yuan predicts that a non-zero gluon Sivers function will produce a finite transverse

SSA for color-singlet J/ψ production [16] in $p+p$ collisions, but the asymmetry should vanish for color-octet production [14] in $p+p$ due to cancelation between initial- and final-state effects, while a non-zero asymmetry for J/ψ production in SIDIS is only expected within the color-octet model.

It should be noted that the relationship between the transverse SSA and the production mechanism is not quite as simple in the collinear higher-twist approach, with partial but not full cancelation of terms [17] in the cases where the asymmetry uniformly vanishes in the TMD approach presented by Yuan. Another important point to note regarding the TMD as compared to the collinear, higher-twist approach is that very recent theoretical work [18] suggests that factorization of hard processes in perturbative QCD (pQCD) into transverse-momentum-dependent distribution and fragmentation functions convoluted with partonic hard-scattering cross sections is not valid for processes involving more than two hadrons. Thus, in the process $p+p \rightarrow J/\psi + X$ a gluon Sivers function may not be well defined; however, the definition within a factorized pQCD framework of the corresponding trigluon correlation functions in the collinear, higher-twist approach is believed to be valid.

2. Analysis

2.1. Measuring Transverse Single-Spin Asymmetries

Measurements were carried out by the PHENIX experiment at RHIC, where the cross section and polarization of J/ψ mesons in $\sqrt{s} = 200$ GeV $p+p$ collisions have also been measured [19, 20]. At forward and backward rapidities, $J/\psi \rightarrow \mu^+\mu^-$ were measured with two muon spectrometers [21], for $1.2 < |y| < 2.2$ and $\Delta\phi = 2\pi$, using data from the 2006 and 2008 RHIC runs. At midrapidity, asymmetries were studied via $J/\psi \rightarrow e^+e^-$ with the central arm spectrometers [22], for $|y| < 0.35$ and $\Delta\phi = 2 \times \frac{\pi}{2}$, using data from the 2006 RHIC run.

Our measurement is performed in two separate hemispheres referred to as 'left' and 'right' where left is defined as the axis which forms a right-handed coordinate system with the beam momentum vector and one of the spin orientations, denoted as $\uparrow$. For a vector $\vec{S}$ in the direction of the $\uparrow$ spin and beam momentum $\vec{P}$, left is defined as $\vec{p} \cdot \left(\vec{S} \times \vec{P}\right) > 0$ with $\vec{p}$ being the momentum vector of the outgoing particle.

The left-right transverse SSA can be extracted using Eq. (1). This equation applies to particle yields observed to the left side of the polarized beam.

$$A_N = \frac{f}{\mathcal{P}} \frac{(\sigma^\uparrow - \sigma^\downarrow)}{(\sigma^\uparrow + \sigma^\downarrow)}, \tag{1}$$

where $\sigma^\uparrow(\sigma^\downarrow)$ represents the production cross section with beam polarized in the $\uparrow$ ($\downarrow$) direction, integrated over the left hemisphere, and $\mathcal{P}$ is the beam polarization. An overall minus sign is required for A_N on the right side of the polarized beam.

The geometric scale factor f corrects for the convolution of an azimuthal asymmetry with detector acceptance. For a sinusoidal asymmetry, as generated by the Sivers function, the factor becomes

$$f = \left(\frac{\int_0^\pi \varepsilon(\phi) \sin\phi d\phi}{\int_0^\pi \varepsilon(\phi) d\phi} \right)^{-1}, \tag{2}$$

where ϕ is the azimuthal angle between the outgoing particle and the proton spin, and $\varepsilon(\phi)$ is the efficiency for detecting a J/ψ at a given ϕ. The limits of integration correspond to the hemisphere in which the measurement is being made.

Both proton beams in RHIC were polarized. Single-spin asymmetries explicitly including the spin orientations of both beams, Eq. (1) can be rewritten as:

$$A_N = \frac{f}{\mathcal{P}} \frac{(\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}) - (\sigma^{\downarrow\uparrow} + \sigma^{\downarrow\downarrow})}{(\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}) + (\sigma^{\downarrow\uparrow} + \sigma^{\downarrow\downarrow})}$$

$$= \frac{f}{\mathcal{P}} \frac{(N^{\uparrow\uparrow} + \mathcal{R}_1 N^{\uparrow\downarrow}) - (\mathcal{R}_2 N^{\downarrow\uparrow} + \mathcal{R}_3 N^{\downarrow\downarrow})}{(N^{\uparrow\uparrow} + \mathcal{R}_1 N^{\uparrow\downarrow}) + (\mathcal{R}_2 N^{\downarrow\uparrow} + \mathcal{R}_3 N^{\downarrow\downarrow})}, \tag{3}$$

where $N^{\uparrow\uparrow}, N^{\uparrow\downarrow}, N^{\downarrow\uparrow}$ and $N^{\downarrow\downarrow}$ are the experimental yields in each spin configuration, and $\mathcal{R}_1 = \mathcal{L}^{\uparrow\uparrow}/\mathcal{L}^{\uparrow\downarrow}$, $\mathcal{R}_2 = \mathcal{L}^{\uparrow\uparrow}/\mathcal{L}^{\downarrow\uparrow}$ and $\mathcal{R}_3 = \mathcal{L}^{\uparrow\uparrow}/\mathcal{L}^{\downarrow\downarrow}$ are ratios of the provided luminosities $\mathcal{L}$ in each spin orientation.

Beam polarizations at RHIC are measured by a carbon target polarimeter [23] and a hydrogen jet polarimeter [24]. During the 2006 run the average transverse beam polarizations were 0.53 ± 0.02(syst.)(clockwise) and 0.52 ± 0.02(syst.)(counterclockwise).

Fill-to-fill variation of beam polarization was ± 0.03 (1 σ) for the clockwise beam and ± 0.04 (1 σ) for the counterclockwise beam. There is an additional systematic uncertainty of 3.4% correlated between the two beams. The average beam polarizations during the 2008 run were 0.48 ± 0.02(syst.)(clockwise) and 0.41 ± 0.02(syst.)(counterclockwise) each with a fill-to-fill variation of ± 0.04 (1 σ), and with an additional systematic uncertainty of 3.0% correlated between the beams.

For statistically limited measurements it may be impossible to measure asymmetries using separate yields based on the spin orientation of both beams. In this case we can eliminate all explicit uses of the relative luminosity and calculate a single asymmetry for both the left and right hemispheres using

$$A_N = \frac{f'}{\mathcal{P}} \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}. \tag{4}$$

The geometric scale factor

$$f' = 2 \left(\frac{\int_0^{\pi} \varepsilon(\phi) \sin\phi d\phi}{\int_0^{\pi} \varepsilon(\phi) d\phi} - \frac{\int_{\pi}^{2\pi} \varepsilon(\phi) \sin\phi d\phi}{\int_{\pi}^{2\pi} \varepsilon(\phi) d\phi} \right)^{-1} \tag{5}$$

2.2. Analysis Method for $J/\psi \rightarrow \mu^+\mu^-$

Transverse single-spin asymmetries for the $J/\psi \rightarrow \mu^+\mu^-$ decay channel were determined by subtracting a background asymmetry from the inclusive signal as

$$A_N^{J/\psi} = \frac{A_N^{Incl} - r \cdot A_N^{BG}}{1 - r}, \tag{6}$$

where the A_N values on the right-hand-side were calculated using Eq. (3). The asymmetry A_N^{Incl} is for oppositely-charged muon pairs in the invariant mass range $\pm 2\sigma$ around the J/ψ mass (where σ is the mass resolution of the detector), and A_N^{BG} is the asymmetry for oppositely-charged muon pairs in the invariant mass range 2.0(1.8 for 2006) $< m$ (GeV/c^2) < 2.5 along with charged pairs of the same sign in invariant mass range 2.0(1.8 for 2006) $< m$ (GeV/c^2) < 3.6.

Measured values of A_N^{BG} and the background fraction r can be found in [25]. A geometric scale factor from 2006 data of $f = 1.57 \pm 0.04$ was determined from J/ψ azimuthal distributions in data and was found to be independent of p_T within statistical uncertainties. The geometric scale factors from 2008 were $f = 1.64 \pm 0.01$ for the clockwise circulating beam and $f = 1.56 \pm 0.01$ for the counter-clockwise circulating beam.

2.3. Analysis Method for $J/\psi \rightarrow e^+e^-$

For the RHIC luminosities and store lengths during the 2006 run there were too few J/ψs detected in the PHENIX central arms to calculate a separate asymmetry for each store. For a statistically limited measurement we do not calculate $\mathcal{R}_i$, f_i, and $\mathcal{P}_i$ for all i but assume that the measurement can be made as

$$A_N = \frac{\langle f \rangle \sum_{i=1}^{n} \left(N_i^{\uparrow} - \langle \mathcal{R} \rangle N_i^{\downarrow} \right)}{\langle \mathcal{P} \rangle \sum_{i=1}^{n} \left(N_i^{\uparrow} + \langle \mathcal{R} \rangle N_i^{\downarrow} \right)}, \tag{7}$$

where the brackets denote a luminosity-weighted average over the course of the measurement. In order for the same physical observable to be calculated by this expression without additional systematic uncertainty we must have $\mathcal{R}_i = \langle \mathcal{R} \rangle$, $f_i = \langle f \rangle$, and $\mathcal{P}_i = \langle \mathcal{P} \rangle$ for all i.

The background fraction from continuum pairs can be found in [25]. An overall dilution of the signal is included assuming that A_N^{BG} =0. Geometric scale factors used in the analysis are determined from simulation. A geometric scale factor are 1.62 ± 0.01 for $0 < p_T$ (GeV/c) < 6, 1.61 ± 0.01 for $0 < p_T$ (GeV/c) < 1.4 and 1.70 ± 0.02 for $1.4 < p_T$ (GeV/c) < 6.

3. Results and summary

Figures 1 and 2 present the measured transverse single-spin asymmetry in J/ψ production versus x_F, and Fig. 2 shows the measured transverse SSA at different rapidities as a function of p_T.

As the functional form of the asymmetry in x_F and p_T is completely unknown, no correction has been made for potential smearing effects. A simulation study was performed assuming a linear dependence of A_N on x_F, and it was found that smearing effects were less than 10% of the value of the input asymmetry. More detail description for the systematic errors is in [25].

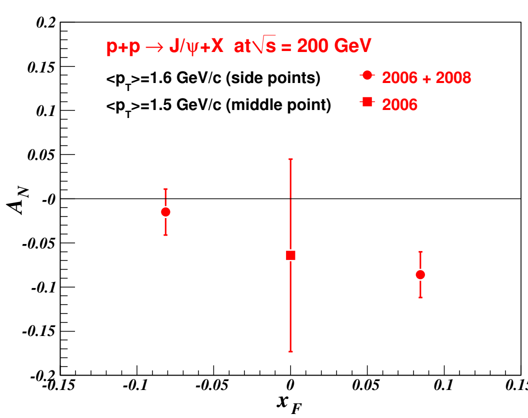

Figure 1. (color online) Transverse single-spin asymmetry in J/ψ production as a function of x_F for combined 2006 and 2008 data sets.

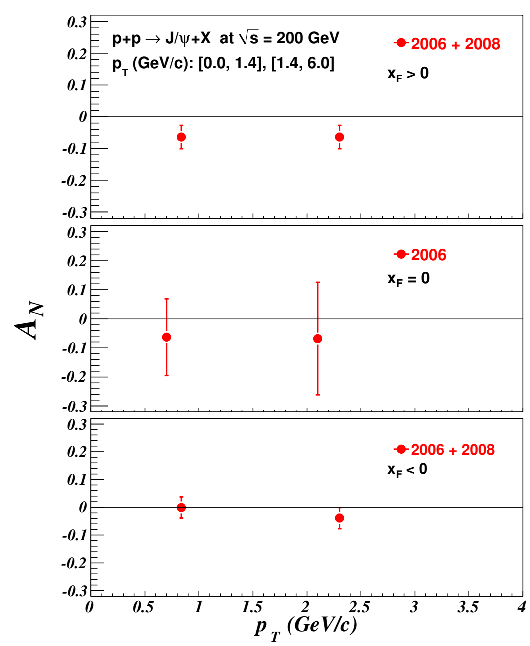

Figure 2. (color online) Transverse single-spin asymmetry in J/ψ mesons ploted against J/ψ transverse momentum.

The measured asymmetry at forward x_F is negative, -0.086 $\pm$ 0.026 $\pm$ 0.003, with a statistical significance from zero of 3.3σ, suggesting a non-zero trigluon correlation function in transversely polarized protons and, if well defined as a universal function in the reaction $p+p \to J/\psi + X$, a non-zero gluon Sivers function. A non-zero transverse SSA in J/ψ production in $p+p$ generated by gluon dynamics may seem surprising given the SSAs consistent with zero in midrapidity neutral pion production at PHENIX [26] and semi-inclusive charged hadron production at COMPASS [27]. However, the details of color interactions have been shown to play a major role in SSAs [18], so further theoretical development will be necessary before we fully understand the relationships among these measured asymmetries. As discussed in ref. [13], a non-zero transverse SSA in J/ψ production in polarized proton-proton collisions generated by a gluon Sivers TMD would be evidence against large contributions from color-octet diagrams for J/ψ production. If a gluon Sivers TMD is in fact well defined and non-zero, a new experimental avenue has been opened up to probe the J/ψ production mechanism, a long-standing question in QCD. As discussed in Section 1, there is a relationship between the SSA and the production mechanism of the J/ψ in the collinear, higher-twist approach, but it is not as simple as in the TMD approach.

Future $p + p$ data from RHIC are expected to improve the precision of the current measurement, and a similar measurement for J/ψ production in SIDIS with a transversely polarized target could shed further light on the production mechanism, as [13] predicts a vanishing asymmetry for the color-singlet model in SIDIS but non-zero asymmetry for the color-octet model. While no rigorous quantitative calculations are presently available for either collision system, we anticipate that future theoretical calculations will provide more detailed guidance on the implications of the present results.

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